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MOISTURE EFFECTS AND PEEL TESTING OF POLYMETHACRYLIMIDE FOAM AND HONEYCOMB CORE IN SANDWICH/SKIN STRUCTURES

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ABSTRACT

One of the greatest concerns of the aerospace materials engineer is how a manufactured final part will change structurally, dimensionally, and weight wise during its lifetime on an aircraft. Polymethacrylimide (PMI) foam has been chosen as a core material for use on the Army's Advanced Composite Airframe Program (ACAP), and is a candidate for use in other current and future Army helicopters (JVX, LXH). The main objective of this paper is to answer a few of the questions concerning structural integrity, dimensional stability, and weight gain of this closed cell thermoplastic structural foam by processing typical sandwich/skin structures, and determining the effects of moisture absorption on peel strength. Results of the PMI foam's exposure to the combined effects of elevated temperature and high humidity conditions were compared directly to identical sandwich/skin constructions using aramid honeycomb core in both 4 and 6 lb/ft^2 densities, used widely by the aerospace industry.

Polymethacrylimide foam cores and honeycomb cores were used both in the "as-is" condition received by the manufacturers, and in an annealed or heat treated condition prior to layup of the sandwich constructions to determine their respective dimensional stability during a standard autoclave curing cycle. Two 350^oF cure structural film adhesive prepregs were used for autoclave bonding $\pm 45^o$ S-2 glass/epoxy precured facesheets onto both the foam and honeycomb constructions to determine their respective surface bonding ability and relative moisture barrier properties. The cured sandwich panels were then finally machined to ASTM D 1781 climbing drum peel test specimens and subjected to 95% relative humidity at 160^oF for exposures up to 720 hours and subsequent redry both with and without RTV-sealed edges to determine comparative moisture weight gains and their effect on peeling torque.

Results showed that water uptake in PMI foam core sandwich structures tested was significantly higher than honeycomb cores of similar density. However, facesheet-to-core peeling torques did not suffer due to this migration of moisture.

INTRODUCTION

Sandwich/skin composite structures have become an increasingly popular structural consideration vs. monoqoque or skin/skeleton designs because of the dramatic strength/stiffness-to-weight improvements that are achievable with organic matrix materials. Applications include use in Army helicopter rotor blades, fuselages, cargo floors, and tail booms, as well as potential use in tactical shelters and high mobility ground vehicles. For aircraft structures in particular, the most commonly used structural core materials have been honeycombs such as "Nomex" a phenolic-coated aramid paper produced by DuPont and manufactured into honeycomb form by Hexcel Corp. Until recently, structural foam cores could not compete on an equal density basis with Nomex, while maintaining acceptably high compressive and peel strengths.[1]

Polymethacrylimide (PMI) foam, manufactured in West Germany by Rohm and Haas, and marketed as "Rohacell" foam, currently offers the highest compressive strength of the low density foam core materials (Figure 1).

Potential advantages of using PMI foam versus honeycomb are listed below:

1. Lower sheet stock cost - aerospace WF grades are presently about 1/3 less than the HRH-10 grades of similar density (Figure 2).

2. Ease of machinability - ability to rough cut foam to approximate shape, then compression mold to final net shape, for complex contour part production without requiring expensive 5-axis machining. Low cost foam mandrels may also be machined, then used for filament winding, braiding, or tape laying operations.[2]

3. When annealed, the isotropic WF grade of PMI foam maintains 0^o and 90^o compressive strength to 350^oF.[6]

4. Thermal expansion of PMI foam at elevated temperatures[3,4] provides internal pressure to help stabilize skins/adhesives during co-curing operations.

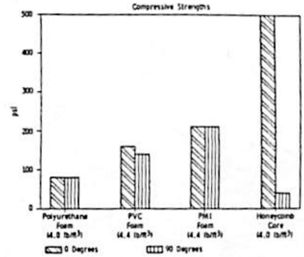


Figure 1. 0° & 90° Compressive strengths of aircraft grade core materials.

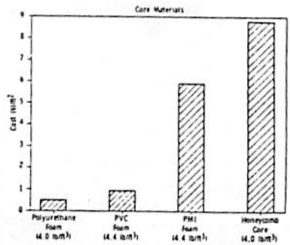


Figure 2. Cost comparison of aircraft grade core materials.

Three inherent disadvantages of PMI foam are the following:

1. Water absorption is comparatively higher than all of the other aircraft grade foams and honeycomb referenced in this paper.
2. It will burn with a slightly smokey flame.[5]
3. Because of the foam's relatively small cell size, bonding ability to substrates can be difficult.[6,7,8] (Improved bonding can be achieved through the use of needle rollers which are available at the foam supplier).

In this study, aramid honeycomb is compared directly to the PMI foam so that the materials engineer will have a more tangeable understanding of what to expect for dimensional stability during the annealing and autoclave processing, as well as subsequent relative weight gains and peel strengths when these cores are employed as part of an actual sandwich/skin structure.

EXPERIMENTAL

The materials used in the sandwich/skin laminates, along with their manufacturers, are listed in Table 1. 3M's SP-250 S-2 glass/epoxy prepreg, in a two-ply $\pm$ 45° orientation, was used for sandwich skin facesheets on all laminates. Forty eight 2 ft. x 2 ft. facesheets were precured in an autoclave using the manufacturer's standard cure cycle, then lightly sanded on one side to improve subsequent bonding to the cores. All 2 ft. x 2 ft. core materials, including two densities of Nomex aramid honeycomb HRH 10-4 and HRH 10-6 (4 and 6 lb. density), were cut down the middle so that one 1 ft. x 2 ft. core half could be dried and annealed while its other half received no treatment. the PMI halves were also needled using a specially built hand needle roller provided by the foam supplier. The "pretreated" heating cycle included 72 hours at 150°F followed by 36 hours of annealing at 350°F in an air circulating oven.[6,10] Even though the annealing acutally takes place only in the PMI foam, the honeycomb was also given the same treatment. These cores were then remated with their untreated other halves, labelled, and placed in polyethylene pouches to await final autoclave processing. It was noted during the rematching of halves that the pretreated foam was a uniform pale yellow compared to the milk white untreated half. The pretreated honeycomb had darkened from a light amber to a brown color. Also noted was an average .11 in./ft. lengthwise contraction or shrinkage of the PMI foam and a corresponding average .12 in./ft. lengthwise expansion of the honeycomb.

Table 1 MANUFACTURERS OF MATERIALS USED

Rohacell Foam	Mfd. by Rohm & Haas, West Germany Distributed in U.S. by Cyro Ind., Orange, CT
Nomex Honeycomb	Mfd. by Hexcel Corp., Casa Grande, AZ
Scotchply Skins AF-147 Film Adhesive	Mfd. by 3M Corp., St. Paul, MN
FM 300-K Film Adhesive	Mfd. by American Cyanamid, Havre De Grace, MD

With the cores ready for sandwich/skin construction, two structural film adhesive prepregs with scrims were taken out of the freezer for overnight thawing to room temperature in their bags so that condensation would not form on the adhesives. American Cyanamid FM-300K and 3M AF-147, both prepregs approximately .08 lbs/ft.², had been previously identified as having better than average moisture resistance.[11] The layups were done on polyvinylflouride (PVF) release film covered 3/8" T-6 aluminum caul plates, overwrapped with bleeder-release cloth and burlap. Because of the honeycomb core's relatively weak transverse compressive strength, extra metal strips were cut and placed around the perimeters of each construction to prevent "cave-in" of the sides due to autoclave pressure during cure. Nylon vacuum bags with glands were then heat sealed around each layup, and vacuums applied. Since both film adhesives used shared a common cure cycle, all constructions were autoclave cured under the same conditions (Figure 3).

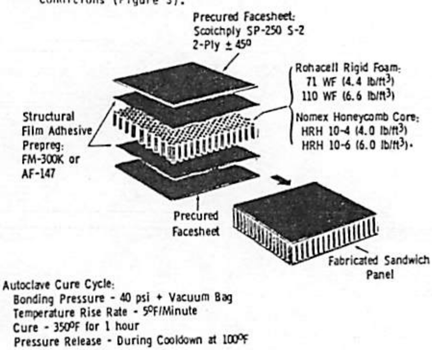


Figure 3. Sandwich/skin constructions.

After the cure cycle, the sandwich/skin laminates were removed from their wrappings, marked, and relabelled (Figure 4) for diamond wheel machining into 3" x 12" climbing drum peel test specimens as outlined in ASTM D-1781. When unwrapped, it was observed that the PMI foam sandwiches that had not undergone the redry and annealing pretreatment had compressed in a concave fashion, while their matching pretreated halves appeared unaffected. Average thickness from specimens of the cured laminates are shown in Figure 5. The honeycomb cores, both with and without heat pretreatment, retained very close thickness dimensions (Figure 6).

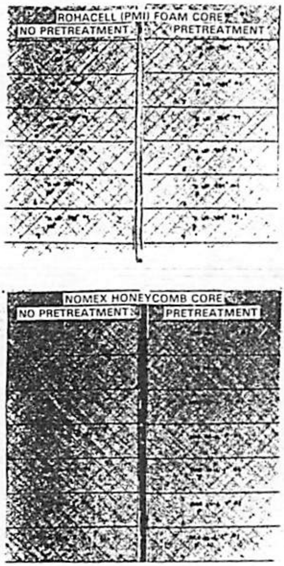


Figure 4. Labelled sandwich/skin laminates prior to machining into climbing drum peel specimens.

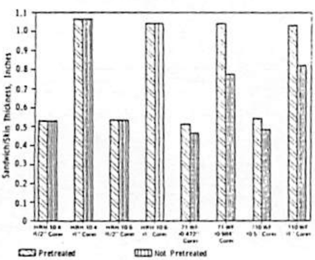


Figure 5. Effect of core pretreatment on thickness of sandwich/skin constructions after autoclave curing.

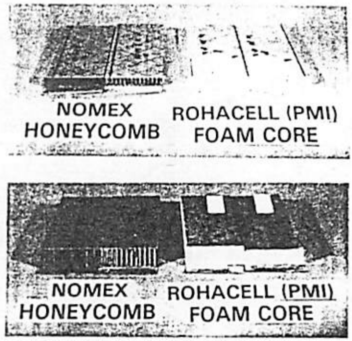


Figure 6. Effect of "Pretreated" versus "Not Pretreated" core materials on final sandwich/skin thickness.

Humidity Conditioning

Each sandwich/skin construction was divided into seven groups with three specimens per group, for humidity conditioning (Table 2). Specimens 1-12 were unsealed along the sides because of the relatively short times of exposure and to help determine water weight gain through the unprotected foam. Specimens 13-21 were sealed with MIL-A46106A type 1 general-purpose RTV silicone adhesive sealant. The sealant was used to help determine water weight gain through the facesheet sides of the specimens over extended exposure times.

Table 2 NUMBERING CLASSIFICATION FOR EACH CORE MATERIAL

P = Pretreatment	NP = No Pretreatment
TOTAL 21	TOTAL 21
3" x 12" Climbing Drum Peel Test Specimens	3" x 12" Climbing Drum Peel Test Specimens

Pretreatment - Core Heat Treatment (72 Hours at 150°F, Followed by 36 Hours at 350°F)

Pretreated and Not Pretreated

Specimens 1, 2, 3			Test As-Is
Exposure @95% R H and 160°F	Unsealed	4, 5, 6	80 hours
		7, 8, 9	160 hours
		10, 11, 12	160 hours, subsequently redry 72 hr @140°F
	RTV Sealed	13, 14, 15	360 hours - (15 days)
		16, 17, 18	720 hours - (30 days)
		19, 20, 21	720 hours, subsequently redry 72 hr @140°F

EXAMPLE

Sandwich/Skin Panels	
71 WF 0.472" #1 P	71 WF 0.472" #1 NP
1	1
2	2
3	3
4	4
5	5
6	6
7	7
71 WF 0.472" #2 P	71 WF 0.472" #2 NP
8	8
9	9
10	10
11	11
12	12
13	13
14	14
71 WF 0.472" #3 P	71 WF 0.472" #3 NP
15	15
16	16
17	17
18	18
19	19
20	20
21	21

24"

24"

A Blue M environmental chamber, model #AC-7602HA, was set at 95% relative humidity and 160°F for all exposures. Except for specimens 1-3, which were baseline specimens that had no exposure in the chamber, each of the 336 specimens tested, both with and without pretreatment, was weighed before and after exposure, and the difference recorded. In addition, one square foot of each separate material used was weighed out and subjected to long-term (90 day) humidity exposure. The prepreg skins and structural film adhesives were precured prior to testing. This testing was carried out to determine the contributing effects of moisture absorption by each component of the composite sandwich/skin laminate.

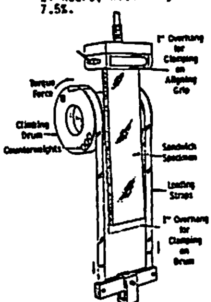
Climbing Drum Shear Peel Testing

After humidity exposures, each set of specimens was bagged in a polyethylene pouch and transported to ARDEC for climbing drum peel testing. The ASTM D1781 procedure was followed using a Custom Scientific Inc. climbing drum peel apparatus and a standard Instron tensile testing machine (Figure 7). A crosshead speed of 1 inch/minute was used for an effective specimen peel rate of 4 inches/minute on the drum. The chart speed was set at 1 inch/minute. The load required to bend and peel the adherend as well as the load required to overcome the resisting torque of the climbing drum was recorded on the chart paper for each specimen.

RESULTS AND DISCUSSION

Unprotected Core Material Weight Gain

Unprotected 1 ft.^{2} core materials of both Rohacell and Nomex were found to readily accept moisture, but the relative differences in percent weight gain were significant. When they were subjected to long-term humidity exposure, (Figure 8), the Nomex showed a peak weight gain after 30 days of 3.7 - 3.8%, and thereafter a leveling off. The Rohacell varied from 4.4% weight gain after 30 days with the 71 WF .472" core, to as much as 10.9% with the 110 WF 1" core, after which the foam started to lose weight. Because of the 4.4 - 10.9 range in weight gains, it was probable that the lower density foams had reached their saturation point and had started losing weight well before the 30 day weighings. This was confirmed by oven drying (Figure 9) followed by a 72 hour ambient temperature stabilization period, and re-exposure of the core materials, (Figure 10), for a short term under identical humidity conditions but taking data points more often. The Nomex rate of moisture pickup dropped off markedly after 2-4 hours exposure and did not exceed a 3.4% weight increase. The Rohacell weights began to level off only after 24 hours, with weight increases ranging from 7.1 - 7.5%.



THIS TEST MEASURES THE TORQUE TO PEEL THE FACING FROM THE CORE. THE PEELING TORQUE DEPENDS ON THE RESILIENCE OF THE ADHESIVE BOND AND ON CORE STRENGTH. IT IS CALCULATED AS FOLLOWS:

$$\bar{T} = \frac{(r_o - r_i)(F_p - F_o)}{W}$$

WHERE:

$\bar{T}$ = AVERAGE PEEL TORQUE, in.-lb/in. OF WIDTH

r_o = RADIUS OF FLANGE, INCLUDING ONE HALF THE THICKNESS OF THE ADHEREND BEING PEELED, in.

r_i = RADIUS OF DRUM PLUS ONE HALF THE THICKNESS OF THE ADHEREND BEING PEELED, in.

F_p = AVERAGE LOAD REQUIRED TO BEND AND PEEL ADHEREND PLUS THE LOAD REQUIRED TO OVERCOME THE RESISTING TORQUE, lb

F_o = LOAD REQUIRED TO OVERCOME THE RESISTING TORQUE, lb

W = WIDTH OF SPECIMEN, in.

Figure 7. Climbing drum peel test (ASTM D 1781, MIL-STD 401B).

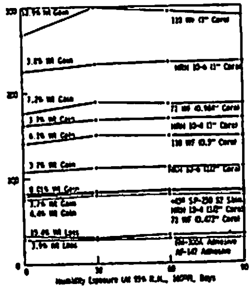


Figure 8. Effect of prolonged humidity exposure on 1 ft^2 sandwich/skin components.

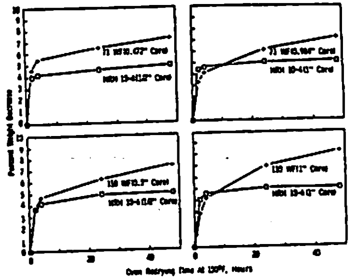


Figure 9. Effect of redry on 1 ft^2 cores after 90-day humidity exposure.

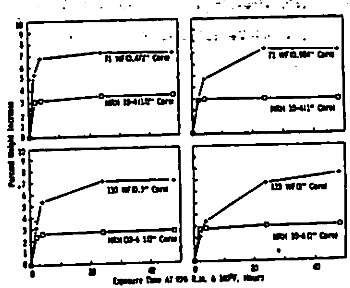


Figure 10. Effect of short-term humidity exposure on 1 ft^2 cores.

Sandwich/Skin Weight Gain - Unsealed Edges

The top halves of Figures 11-14 show the corresponding weight changes of the 3" x 12" climbing drum peel specimens with unsealed edges when exposed to 80 and 160 hours of 95% R.H. and 160°F, and subsequent air circulating oven redry at 140° for 72 hours. The sandwich/skin specimens with pretreated core material registered high weight gains and an equal or higher rate of moisture uptake. At the 160 hour mark, peak percent weight gain for the Nomex was 1.5% for

specimens with pretreated cores and 1.0% for "as-is" or untreated core specimens. There was no significant difference in percent weight gain between the Nomex 1/2" and 1" cores. During the 72 hour redry at 140°F, all specimens returned to or went below their weights as recorded just prior to humidity exposure.

For the Rohacell, peak percent weight gain was 3.2% for specimens with .984" and 1" pretreated cores, double that of the Nomex counterparts, and up to 2.5% for the "as-is" or untreated core specimens. Also, there was a significant difference in the Rohacell thickness-to-percent weight gain relationship, with the thicker cores picking up more moisture. During the subsequent redry, only one specimen returned to its original weight, revealing the foam's greater moisture retention in a sandwich/skin laminate.

<u>Sandwich/Skin Weight Gain-RTV Sealed Edges</u>

The bottom halves of Figures 11-14 show the corresponding weight changes of the climbing drum specimens with RTV-sealed edges when exposed to 360 and 720 hours of 95% R.H. and 160°F, and subsequent redry. Since the edges were sealed off, moisture could only be absorbed through the facings of the sandwich. At the 720 hour mark, peak weight gains for the Nomex were 1.9% for the pretreated HRH 10-4, both 1/2" and 1" core thickness, and up to 2.2% for the HRH 10-6 core. The 72 hour redry took all Nomex specimens back to within .5 grams of the weights before humidity exposure.

For the Rohacell, peak percent weight gain was 4.4% for the pretreated 71 WF .984" core and 6.6% for the 110 WF 1" core. Again, the increase in moisture weight gain due to the thickness of the foam was much more of a factor than with the Nomex. The thicker foams absorbed more moisture and retained it after 72 hour redry than the thinner foams in a sandwich/skin laminate.

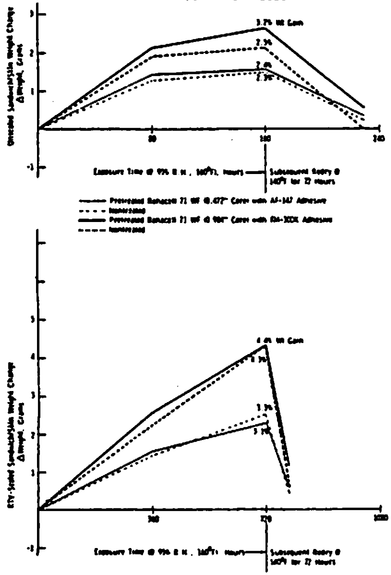


Figure 11. Water weight gain of climbing drum peel specimens - Rohacell 71 WF.

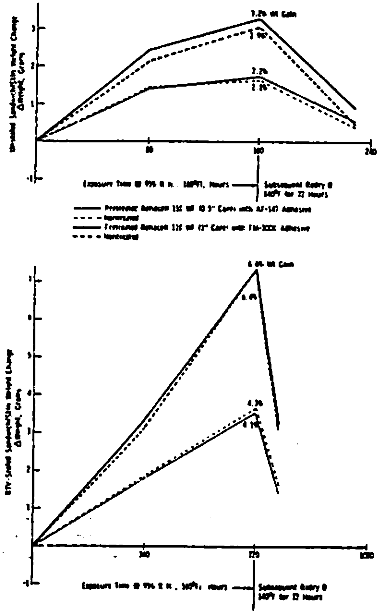


Figure 12. Water weight gain of climbing drum peel specimens - Rohacell 110 WF.

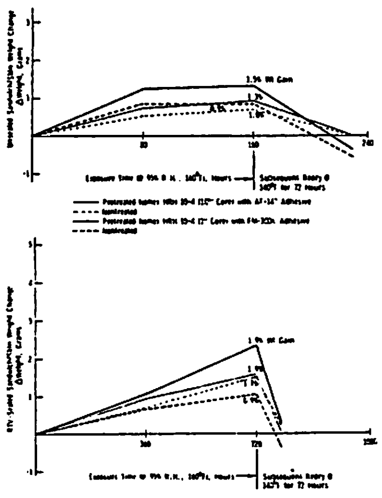


Figure 13. Water weight gain of climbing drum peel specimens - Nomex HRH 10-4.

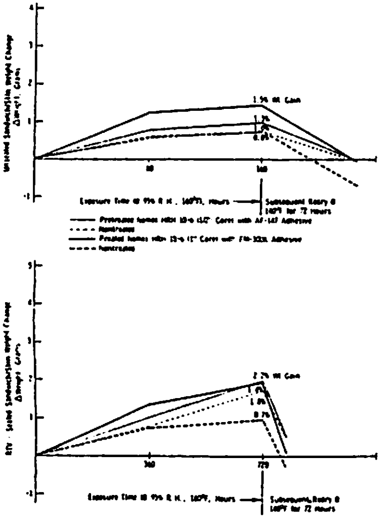


Figure 14. Water weight gain of climbing drum peel specimens - Nomex HRH 10-6.

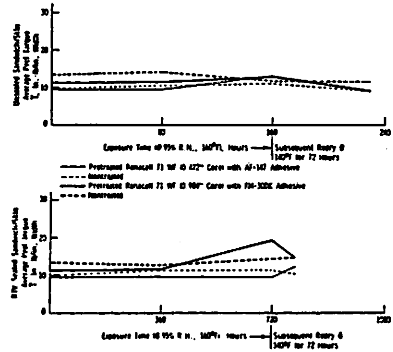


Figure 15. Average peeling torque of climbing drum specimens - Rohacell 71 WF.

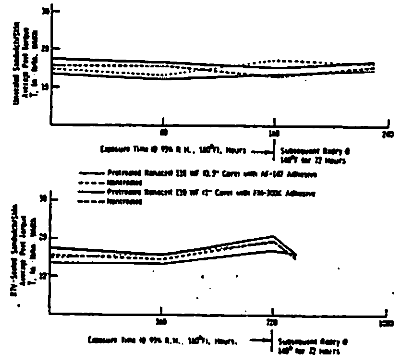


Figure 16. Average peeling torque of climbing drum specimens - Rohacell 110 WF.

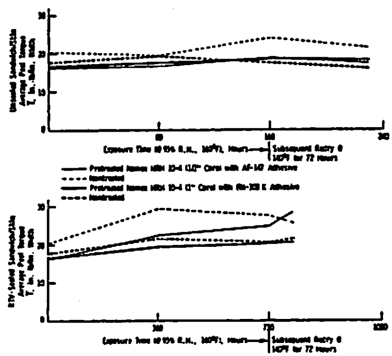


Figure 17. Average peeling torque of climbing drum specimens - Nomex HRH 10-4.

Average Peel Torque

Since the climbing drum peel test does not discriminate core thickness for determining the peel torque, testing variables were based on core density, core pretreatment, specimen humidity conditioning, and type of structural film adhesive prepreg used.

The type of skin-to-core failures when peeling off skins was significant. Both structural adhesives evaluated bonded better to the Nomex cores than to the Rohacell. For the Rohacell-peeled specimens, the majority of the adhesive was on the skin side rather than on the core. The only evidence of adhesive on the core surface was where small holes were punched through it from the "needling operation", using hand rollers. For the Nomex cores, the adhesive formed a meniscus around each honeycomb cell, which ultimately stayed on the core side.

According to the graphs in Figures 15-18, the trends for the Nomex and Rohacell showed a general increase in peel torque values with humidity exposure time. The AF-147 structural film adhesive performed better for all Nomex specimens, while the FM-300X displayed slightly higher torque values for the Rohacell specimens. The ranges of average peeling torque calculated for the Nomex HRH 10-4 specimens started at 16-20 and spread to 16-29 in. lb/in after exposures. The HRH 10-6 specimens started at 21-23 and fanned out to a range of 16-32 in. lb/in. Rohacell 71 WF average torque values started at a range of 9-13 and changed only slightly to 9-19 in. lb/in. The 110 WF foam values started out at 13-17 and varied only to 13-21 in. lb/in.

From these sandwich/skin test results, the 71 WF specimens averaged about 57% of the HRH 10-4 specimen peel torque, while specimens with 110 WF cores averaged about 67% of the HRH 10-6 core peel torque. There were data points indicating as much as a 3X improvement in average peeling torque with

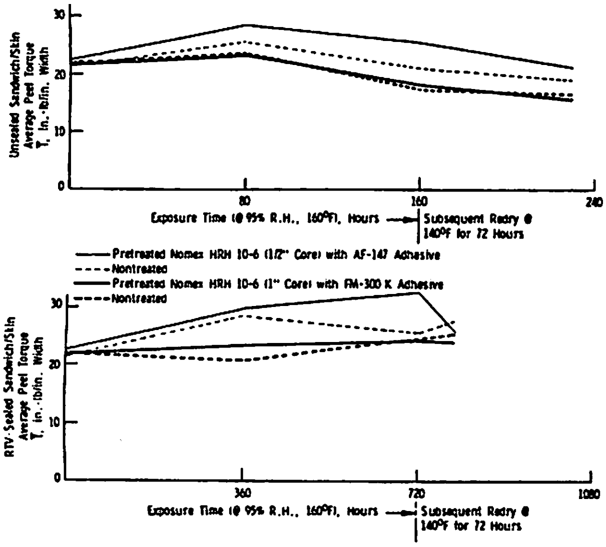


Figure 18. Average peeling torque of climbing drum specimens - Nomex HRH 10-6.

the honeycomb specimens over the structural foam counterparts, but the honeycomb core values fluctuated because of a more complex tearing of skin and honeycomb, while the foam sandwiches peeled much more cleanly.

CONCLUSIONS AND RECOMMENDATIONS

The comparison of moisture weight gains using unprotected core materials only, as well as unsealed and sealed sandwich/skin laminates typical of candidate composite aircraft structures, provided a more realistic guide for understanding how the moisture is absorbed, how much moisture is absorbed and released for given exposures, and its effect on structural integrity.

The results of this study showed that moisture absorption did not effectively decrease the peel torques on the sandwich/skin specimens but actually increased them. A reason for his behavior may be a plasticizing effect or reduced brittleness that the moisture imparted to the sandwich/skin laminates.[12] The moisture also acts to relieve stress concentrations that may be present at the skin/adhesive/core interface.

Since moisture uptake was substantial for the unprotected foam in particular, the need for increased moisture resistance in the skin adhesive bonding film became more significant. The two film adhesives used had very similar weight gains with respect to exposure time, and were found to be compatible with both cores. In the foam specimens, the AF-147 film adhesive was better able to flow into the cell structure and needled holes of the foam core than the FM-300K, but the FM-300K resultant peel torques were marginally higher.

The Nomex honeycomb proved to be superior in moisture weight gain and peeling torque for both densities tested. For Rohacell applications where weight stability is critical and high humidity exposure is significant, it is recommended that lower density and thinner cores be used to minimize weight gain. Also recommended is further study in improved moisture barrier resins and prepregs compatible with the PMI foam. For most applications, however, where a hot wet environment is not a concern, or where the skin thicknesses are greater, the ease to machine and form heat treated PMI foam into complex contour and tapered shapes will continue to be an asset.

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